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MECHANISMS OF AEROSOL PARTICLE DISPERSION

IN THE FREE ATMOSPHERE

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MECHANISMS OF AEROSOL PARTICLE DISPERSION IN THE FREE ATMOSPHERE

by

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MECHANISMS OF AEROSOL PARTICLE DISPERSION IN THE FREE ATMOSPHERE

This paper investigates the dispersion in the free atmosphere of solid particles of irregular shape 100-1000 microns in diameter from altitudes of 500-8000 meters, and of spherical particles 30-100 microns in diameter from altitudes of 500-1000 meters.

Luminescent particles of sand and plastic were employed as an indicator. Particle distribution on the earth's surface was studied. Empirical formulas are given which permit computation of the surface concentration of particles which have fallen from an instantaneous point source in a specific distribution according to descent velocity, depending on the altitude of the source and average land velocity. An analysis of the dispersion factors of impurities of K_y and K_z settling in the atmosphere is given.

Introduction

This paper considers the results of experimental investigations of solid particle dispersion from a source located in the free atmosphere. Dispersion of particles in the atmosphere is of important practical interest. Thus, for example, dusting of agricultural crops to eliminate pests or plant diseases is accomplished from an aircraft by scattering the appropriate material. Treatment of reservoirs to prevent development of malaria-carrying mosquitoes, application of trace-element fertilizers, dusting of forests to combat ticks - carriers of encephalitis - and forest pests, etc. are all accomplished in like manner.

Aerosol dispersion at present is accomplished from low altitude and under low wind conditions. As a rule, the powders discharged are semi-dispersed, in connection with which a significant portion of the

material in the form of very small particles is carried for long distances and settles beyond the boundaries of the treated territory.

Knowledge of the scattering mechanisms of various materials in the atmosphere would permit more effective application of the aerosol technique to resolve many problems of the national economy.

The motion of particles released into the atmosphere depends on many factors. It consists of their regular ordered transfer by the wind, as a result of which the entire mass of particles moves in the direction and at the velocity of average wind*; of settling due to the force of gravity and of scattering due to the variability of air currents, of irregular atmospheric movements, as a result of which the volumetric concentration of the particles decreases, and mean distances between them and the overall dimensions of the particle cloud increase. Any increase in the dimensions of the initially dispersed cloud in one or another direction enhances its subsequent scattering due to the fact that such an increase in size permits development of the effect of wind velocity and temperature fluctuations on an even larger scale.

The direct task of this paper was to conduct experimental investigations of settling and dispersion of particles in the atmosphere on a scale of interest for practical application. A wide range of particle sizes characterized by their descent velocities from 0.1 to 3 m/sec was selected for the studies. Each experiment consisted of the fact that a certain quantity of particles were released from an aircraft at a previously specified point. The area of expected particle fall was covered by a network of sticky plates. Upon conclusion of the experiment the plates were collected and the number of particles, which were dyed beforehand by luminophores for identification, settling on them were counted under ultraviolet light. This made it possible to compile a distribution pattern of the particles which settled to the surface of the earth. The drops were laid at altitudes from several hundreds of meters to 8 kilometers. The region in which a discernible surface concentration of particles was observed reached several thousand square kilometers.

The purpose of analysis of the materials was to determine the relationship between the basic characteristics of the trail - the extent of surface concentration of particles and the fallout zone, the position of the zone of maximum concentration, and the extent of dispersion of the surface concentration - on the one hand, and the overall quantity of released particles, wind velocity and descent velocity of the particles in the atmosphere, on the other.

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* By average wind we mean a wind whose velocity and direction are obtained by vector averaging along the vertical between the release point and the surface of the earth.

As a result simple empirical functions were obtained which may be applied to solution of many practical problems. Moreover, an attempt was made to evaluate turbulent scattering factors of impurities in the free atmosphere.

Experimental Procedures

Preparation of luminescent particles of sand. The material used to investigate scattering of heavy particles (settling velocity of more than 1 m/sec) was natural silica sand with an average specific weight of 2.6 g/cm^3 whose typical particle distribution by size is presented in Table 1.

Table 1

Diameter (micron	125—175	175—225	225—275	275—325	325—375	375—425	425—475	475—525	525—575	575—625	625—675
Quantity (%)	2,9	13,5	35,1	18,5	11,9	9,0	3,5	2,5	1,4	0,9	0,8

The sand was scattered in fractions using a vibrating sieve with graduated brass grids. As a result of the scattering fractions were obtained with narrower ranges of sizes. Table 2 presents as an example fractions designated P-250 and P-350.

Table 2

Diameter (mu)		175—225	225—275	275—325	325—375	375—425	425—475	475—525
Quantity (%)	Fraction P-250	10	50	26	10	3	1	0
	Fraction P-350	0	2	13	46	31	7	1

In order to facilitate counting the particles, the sand scattered was colored by luminophores manufactured under the brand "Light Yellow Lumogen" and "Aqua-blue Lumogen". The quantity of lumogen was selected at 50 grams per 100 kilograms of sand. Dying of the sand and the first experiments (1955-56) was accomplished by using agar-agar as a bonding material between the sand and the dye by the method proposed by the Institute of Organic Chemistry of the USSR Academy of Sciences [5], and later without agar-agar. The latest method of dyeing the so-called "dry" method, was developed in the Institute of Applied Geophysics and was first used in experiments in 1958.

Laboratory experiments and field tests indicated that the dry method yields a uniform coloring. The lumogen adheres firmly to the particles, and even prolonged immersion in water does not vary the intensity of illumination. The advantage of the dry method is the much shorter (8-10 times) time for preparing the material. After dyeing the sand is subjected to a second sifting. It should be noted that the sand dyed witha light blue lumogen partially loses its capability to luminesce after prolonged exposure to the sun.

Preparation of luminescent particles of plastic. Particles obtained by polymerization of an emulsion of a methylester of methacrylic acid in water with admixtures of catalyst and emulsifier were used as light particles (settling velocity less than 1 m/sec). A polymethylmethacrylic powder manufactured by the Kharkov plant of dental materials (KhZZM) was used in the experiments with particles less than 100 mu in diameter. This powder is polydispersed (from 5 to 100 mu), and its particles have a regular spherical shape and dye well with luminescent dyes in an alcohol solution. The specific weight of the particles of the emulsified polymethylmethacrylic powder is 1.12-1.16 g/cm^3. The powder is scattered in separate fractions with ranges of 10-45, 45-65, 65-80, and 80-100 microns.

A powder produced by the "Karbolit" plant (Orekhovo-Zuyevo) was used in experiments where larger particles were required. In this case the fractions were separated into 125-150, 150-200, 200-250 and 250-315 microns.

Scattering of the powders was accomplished by vibrating sieves. Table 3 shows the distribution of powder particles by size for fractions of 10-45 and 45-65 microns.

Table 3

Diameter (microns)		<15±7,5	30±7,5	45±7,5	60±7,5	75±7,5
Quantity (%)	Fractions 10-45	22	44	32	2	0
	Fractions 45-65	3	8	53	34	2

The method of dyeing the powder particles of the methylester of methacrylic acid was proposed by A. V. Davanko [2]. A large number of dyes (24) was investigated in the laboratory. However, when preparing large quantities of powder only those which met the most intensive illumination were used (Table 4).

Table 4

Name of dye	Color of luminescence
Rhodamine S	Red
Rhodamine 6Zh	Orange
Auramine	Yellow
Eosin	Orange-rose

The powder was dyed in an alcohol solution. Dyeing standards were established by laboratory experiments - 10 grams of dye mixed in 1.25 liters of alcohol were required per 1 kilogram of powder. The amount of dye was increased to 15 grams when dyeing rhodamine 6Zh. After dyeing the remaining alcohol was pumped out in a Nutsch filter, and the powder was washed with water until a colorless filtrate was obtained and was dried on special racks at a temperature of 30-35°C [1]. The persistence of the dye to solar radiation is important when the colored powders are used are aerosols. Experimental purification indicated that all the rhodamines are sufficiently persistent. Auramine was less persistent.

Dropping the particles. The dyed powder and sand were dropped from various types of aircraft with the help of various devices. The drop system and technique were selected so that the particle source would be as instantaneous and localized as possible. However, even at this initial moment in time the cloud expanded in the direction of aircraft motion, and the length of the cloud was 100-200 meters. With respect to the length of the patch -"the track"-which developed on the ground, this is a very small value (about 0.1 in the experiments with sand and 0.01 in those with plastic), which permits consideration of the point as localized with a rather close approximation.

Specially prepared containers equipped with a parachute were employed for dropping the sand from an aircraft when operating in sparcely populated areas (the 1956 experiments). The container opened at the moment the parachute opened and the sand poured out within 1-2 seconds, and the empty container descended on the parachute. The container opened within 1 second after separation from the aircraft. Special attachments permitted dropping 2-4 containers simultaneously, and the capacity of each of them was 150-200 kilograms. When dropping particles about populated areas (the 1957-1960 experiments) a special casette was used with a capacity of 200-250 kilograms of a sand fraction of 200-300 microns or of 100 kilograms of plastic particles. The powders poured out of the casette within 1-2 seconds.

Description of the target areas. The released particles were captured on previously prepared target areas, on which plywood sheets had been laid out in a definite order. The sizes of the target areas were selected depending on the scale of the experiments. The target areas varied from 20 to 225 km^2 in the experiments with sand particles, and from 3 to 10 thousand km^2 in the experiments with light particles.

The 1955 target area consisted of a small (4 x 5 klm) and large (8 x 10 klm) areas. Its axial line lie along an azimuth of 150°; 17 boundaries passed perpendicular to the axis and four roads were at a certain angle. Orientation of the target area was selected in connection with the fact that data over a number of years indicating that northwest and westerly air currents predominate in the lower part of the troposphere during August in the region of the target area. The boundaries passed within 500 meters of the territory of the small area and the sheets were laid out within 50 meters of the boundaries and the axis. The boundaries passed within one kilometer of the large area and the sheets were laid out within 100 meters.

The area of the 1956 target areas located in the Uzbek SSR was 5 x 5 kilometers (the small target area) and 15 x 15 kilometers (the large target area). The small target area was broken near the entrance to the Ferghana valley. It was a flat rectangular area covered by short grass (5-10 cm). The entire territory of the target area was broken down into regular rectangles with a size of 500 and 250 meters along which sheets were laid out every 50 meters. The large target area was located in the center of the Golodnaya steppe. The terrain here is flat and covered with grass 10-20 cm high. Part of the target area (4 x 6) klm^2 was occupied by a plowed field. The sheets on the territory of the large target area were laid out every 100 meters in straight lines spaced one kilometer apart in a north-south direction.

The area of the target areas was 50 x 75 kilometers and 100 x 100 kilometers when working with light particles (settling velocity from 0.07 to 0.8 m/sec). The first experiments (1957) with the plastic particles from 10 to 300 microns in size were conducted on the territory of the Moscow and Kaluga oblasts. The target area (Figure 1) was broken down into an area of approximately 6500 klm^2, on which five courses were laid out which provided as even a distribution of the sheets as possible. To the left of each course was 350-400 kilometers. There were large forests and fields on the territory of the target area. The relief of the terrain was flat lightly broken by the depressions of small rivers. The sheets were laid out in open places every 1-2 kilometers.

Later experiments (1959-60) with plastic particles 10-80 microns in diameter were conducted on an experimental meteorological polygon of UkrNIGMI (Ukranian Scientific Research Hydrometeorological Institute) with an area of 75 x 50 klm, located in the south of the Dnepropetrovsk oblast. The terrain here is flat and slightly broken; almost all the territory of the polygon is an agricultural region, and only the industrial region of Krivoy Rog is located in its western section. There are 160 observation points located in villages at a distance of 3-10 kilometers from each other on the territory of the polygon. In 1960 the territory of the polygon was increased to 100 x 100 klm. The new boundaries of the polygon occupied the western section of the Dnepropetrovsk, the extreme northern section of

the Kherson and the southern section of the Kirovograd oblasts. The number of observation points was increased to 360. Observation points in the central section of the polygon were located every 3-5 klm, and on the periphery - every 7-10 klm. The observation network, where the sheets were laid out every 2 kilometers, was increased in the center of the polygon at a radius of 20 kilometers.

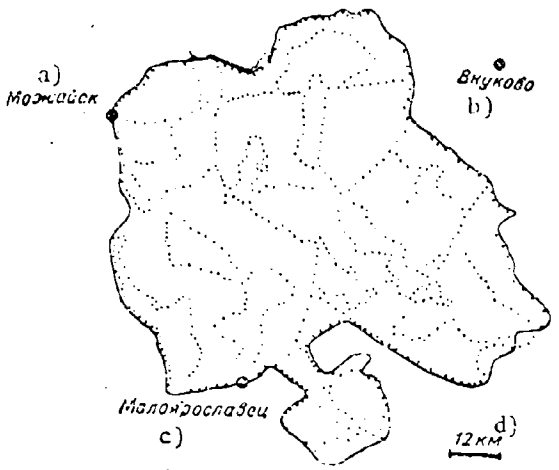

Figure 1
Layout of the 1957 target area.
a) Mozhaisk; b) Vnukovo; c) Maloyaroslavets; d) 12 klm.

Plywood sheets 0.02 and 0.12 m^2 in area were employed to catch the particles. Tracing paper covered with a sticky lubricant consisting of a mixture of resin and castor oil in the proportion 2:3, was glued to the plywood. Such a mixture is not absorbed by the tracing paper and remains sticky on the sheets for several months.

Miscounting the samples. The initial processing of the samples consisted of counting the number of particles which settled on the sheets and in determining the size of these particles. The number of particles was counted visually while the sheet was illuminated by ultraviolet radiation. Disk illuminators having three L-33 fluorescent lamps with filters of UFS-4 UVOIL glass. Besides those indicated, illuminators manufactured on SVDSh-250 and SVD-120 lamps were also used.

The error in counting large particles was 5-10%. Particles less than 100 microns are difficult to see with the unaided eye, and in this case counting was accomplished using four and five-power magnifier with standard calibration. The diameter of the particles was determined with the help of a microscope.

The technique of Aerological Surveys. Aerological surveys during the experiments were conducted first of all to determine the wind profile without consideration of which the experiment could not have been set up, and secondly, to obtain the characteristics of the state of the atmosphere for the period of the experiment. Wind direction and speed at altitudes were measured by the method of single-point pilot balloons. Pilot balloon observations were usually begun 1-2 hours before the drop and were continued during the entire time of particle descent at launch intervals of 30-60 minutes. The point of pilot balloon observations during the 1956-1959 and 1960 experiments was located near the center of the polygon. In 1957 wind sounding was conducted at the Mozhaisk, Vnukova and Maloyaroslavets stations which were located on the periphery of the polygon, 50 kilometers from its center (Figure 1). The pilot balloons were launched within one hour of the periods established on the day before the experiment.

Aircraft sounding of the atmosphere by the standard method was carried out in order to determine the vertical temperatures distribution before and after release of the particles. The results of aircraft flights from the Dnepropetrovsk station were radiosonde launches from the Krivoy Rog station were employed in 1959 to obtain data on the vertical temperature profile.

Results of the experiments. Analysis of the results of aerological surveys. One of the important meteorological parameters during propagation of particles in free atmosphere is the speed and direction of average wind in a given layer.

Analysis of the experimental results indicated that particles fall from the points source takes place in the direction of average wind measured during the experiment in the layer of particle settling. Average wind is calculated from the wind profile by geometrical addition of individual wind vectors at each level.

$$\vec{u} = \frac{1}{H} \sum_{i=1}^{n} \vec{u}_i \Delta z_i,$$

where H is the altitude of particle release, u_i is the wind vector in layer Δz_i, and n is the number of layers.

The direction and speed of average wind during the experiments were rather stable. In most cases average wind varied no greater than 10° in direction and 1 m/sec in speed. In rare cases this variation was 20° and 2-3 m/sec. As an illustration Tables 5 and 6 show values of average wind for observation periods for several experiments.

Table 5

Date	Time of release (hr,min)	H (m)	Period of observations (hr,min)	Average wind: Direction (deg)	Average wind: Velocity (m/sec)
22. IX/1959	10 23	1000	10 00 10 35 11 35 12 35	322 316 302 282	3,7 3,3 3,8 3,2
25. X/1959	13 05	300	12 45 13 32 14 02 15 00	239 258 257 258	5,5 6,7 7,2 6,0
4. IX/1960	12 26	1000	12 07 12 50 13 31 14 09 15 06	256 255 257 263 263	4,6 4,0 4,8 5,6 4,0
5. IX/1960	12 13	1000	12 11 12 52 14 02 15 03 16 00	190 185 171 176 177	5,8 6,2 5,0 5,4 7,2
11. IX/1960	13 30	1500	13 35 14 27 15 35 16 34	299 308 301 297	4,7 3,6 5,0 4,2
12. IX/1960	12 06	1000	12 03 13 05 14 11 15 02	281 285 299 303	5,1 5,4 3,6 3,8

Table 6

Date	Name of station	Periods of observation (hr, min)													
		9 00		10 00		11 00		12 00		13 00		14 00		15 00	
		φ	u	φ	u	φ	u	φ	u	φ	u	φ	u	φ	u
	Maloyaroslavets			146	10,3	133	8,6	141	9,1	129	8,0				
	Vnukovo	132	11,9	144	12,2	144	10,9	131	10,3	136	9,7				
	Maloyaroslavets					201	5,8	202	6,2	213	7,4	201	8,1	194	8,4
	Vnukovo			212	6,0	211	5,7	209	5,5	208	5,6	201	5,9		

Note. ϕ is in degrees; u is in m/sec.

Table 7

Track No.	Experiment No.	Date of Exp.	Time of Release (hr, min)	Initial Experimental Data							Type of Stratification	Results of Experiments				x_{kine}
				H	$\frac{D}{\mu}$	w	Q	a	γ	γ_{100}		x_{max}	q_{max}	σ_y	σ_x	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1	29. III/1956	11 14	500	250	1,35	$1,8 \cdot 10^9$	15				$5,7 \cdot 10^3$	$6,2 \cdot 10^2$	$5,8 \cdot 10^1$	$7,4 \cdot 10^2$	$5,6 \cdot 10^3$
2					300	1,55	$9,5 \cdot 10^8$					$5,1 \cdot 10^3$	$1,4 \cdot 10^3$	$5,9 \cdot 10^1$	$6,2 \cdot 10^2$	$4,8 \cdot 10^3$
3					350	1,80	$3,5 \cdot 10^8$					$4,9 \cdot 10^3$	$9,2 \cdot 10^3$	$2,6 \cdot 10^1$	$4,6 \cdot 10^2$	$4,2 \cdot 10^3$
4	2	11. IV/1956	8 07	1000	250	1,35	$1,8 \cdot 10^8$	5	0,7		III	$4,1 \cdot 10^3$	$1,0 \cdot 10^3$	$3,0 \cdot 10^1$	$6,4 \cdot 10^2$	$3,7 \cdot 10^3$
5					300	1,55	$9,5 \cdot 10^8$					$3,6 \cdot 10^3$	$2,8 \cdot 10^3$	$2,8 \cdot 10^1$	$4,4 \cdot 10^2$	$3,2 \cdot 10^3$
6					350	1,80	$3,5 \cdot 10^8$					$3,4 \cdot 10^3$	$3,4 \cdot 10^3$	$2,5 \cdot 10^1$	$4,4 \cdot 10^2$	$2,8 \cdot 10^3$
7	3	14. IV/1956	5 35	500	200	1,10	$1,8 \cdot 10^8$	4				$1,7 \cdot 10^3$	$3,0 \cdot 10^3$	$3,0 \cdot 10^1$	$3,5 \cdot 10^2$	$1,8 \cdot 10^3$
8					250	1,35	$9,5 \cdot 10^8$					$1,5 \cdot 10^3$	$2,6 \cdot 10^3$	$2,2 \cdot 10^1$	$3,1 \cdot 10^2$	$1,5 \cdot 10^3$
9					300	1,55	$6,1 \cdot 10^8$					$1,4 \cdot 10^3$	$5,0 \cdot 10^3$	$2,0 \cdot 10^1$	$2,2 \cdot 10^2$	$1,3 \cdot 10^3$
10					350	1,80	$6,2 \cdot 10^8$					$1,2 \cdot 10^3$	$2,3 \cdot 10^3$	$2,0 \cdot 10^1$	$1,2 \cdot 10^2$	$1,1 \cdot 10^3$
11	4	14. IV/1956	15 07	1000	250	1,35	$9,5 \cdot 10^8$	3				$2,1 \cdot 10^3$	$1,6 \cdot 10^3$	$3,1 \cdot 10^1$	$2,6 \cdot 10^2$	$2,2 \cdot 10^3$
12					300	1,55	$6,1 \cdot 10^8$					$1,9 \cdot 10^3$	$1,6 \cdot 10^3$	$2,2 \cdot 10^1$	$2,5 \cdot 10^2$	$1,9 \cdot 10^3$
13					350	1,80	$6,2 \cdot 10^8$					$1,7 \cdot 10^3$	$1,1 \cdot 10^3$	$3,1 \cdot 10^1$	$2,2 \cdot 10^2$	$1,7 \cdot 10^3$
14	5	18. IV/1956	5 27	1000	200	1,10	$2,8 \cdot 10^8$	3				$1,8 \cdot 10^3$	$9,5 \cdot 10^3$	$1,8 \cdot 10^1$	$2,8 \cdot 10^2$	$2,7 \cdot 10^3$
15					250	1,35	$1,2 \cdot 10^9$					$1,6 \cdot 10^3$	$4,7 \cdot 10^4$	$2,5 \cdot 10^1$	$2,2 \cdot 10^2$	$2,2 \cdot 10^3$
16					300	1,55	$5,1 \cdot 10^8$					$1,5 \cdot 10^3$	$4,0 \cdot 10^4$	$1,6 \cdot 10^1$	$1,8 \cdot 10^2$	$1,9 \cdot 10^3$
17					350	1,80	$5,8 \cdot 10^8$					$1,3 \cdot 10^3$	$5,5 \cdot 10^4$	$1,5 \cdot 10^1$	$1,2 \cdot 10^2$	$1,7 \cdot 10^3$
18					400	2,00	$3,5 \cdot 10^8$					$1,2 \cdot 10^3$	$5,3 \cdot 10^4$	$1,2 \cdot 10^1$	$6,6 \cdot 10^2$	$1,5 \cdot 10^3$
19	6	21. IV/1956	5 39	1000	250	1,35	$1,2 \cdot 10^9$	4				$2,9 \cdot 10^3$	$1,6 \cdot 10^3$	$3,0 \cdot 10^1$	$4,8 \cdot 10^2$	$3,0 \cdot 10^3$
20					300	1,55	$5,0 \cdot 10^8$					$2,5 \cdot 10^3$	$1,6 \cdot 10^3$	$2,2 \cdot 10^1$	$4,2 \cdot 10^2$	$2,6 \cdot 10^3$
21					350	1,80	$6,5 \cdot 10^8$					$2,3 \cdot 10^3$	$1,6 \cdot 10^3$	$2,0 \cdot 10^1$	$3,5 \cdot 10^2$	$2,2 \cdot 10^3$
22					400	2,00	$3,2 \cdot 10^8$					$2,0 \cdot 10^3$	$1,2 \cdot 10^3$	$2,4 \cdot 10^1$	$2,4 \cdot 10^2$	$2,0 \cdot 10^3$

Table 7 (Continued)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
23	7	21. IV/1956	10	15	1000	200	1,10	1,6·10⁵	4	0,9		III	3,6·10³	5,2·10²	3,5·10²	2,4·10²	3,6·10²
24						250	1,35	1,2·10⁶					3,2·10³	2,8·10²	2,1·10²	3,4·10²	3,0·10²
25						300	1,55	5,0·10⁶					3,0·10³	1,6·10³	3,5·10²	3,5·10²	2,6·10²
26						350	1,80	8,5·10⁶					2,5·10³	2,3·10³	3,0·10²	2,6·10²	2,2·10²
27						400	2,00	3,2·10⁷					2,4·10³	1,4·10³	3,5·10²	2,3·10²	2,0·10²
28	8	26. IV/1956	10	22	1000	400	2,00	1,6·10⁵	10				3,5·10³	1,6·10³	2,5·10²	2,3·10²	5,0·10²
29						450	2,20	3,1·10⁵					3,5·10³	3,2·10³	2,6·10²	2,1·10²	4,5·10²
30	9	26. IV/1956	11	08	1000	400	2,00	1,6·10⁵	6				3,2·10³	7,0·10²	2,8·10²	3,2·10²	3,0·10²
31						450	2,20	3,1·10⁵					3,0·10³	1,2·10³	3,8·10²	2,3·10²	2,7·10²
32						500	2,40	1,0·10⁶					2,9·10³	4,8·10²	2,8·10²	2,2·10²	2,5·10²
33	10	4. V/1956	6	38	1000	300	1,55	8,3·10⁵	5	0,6		IV	1,15·10³	6,2·10²	1,3·10²	1,55·10²	1,20·10²
34						350	1,80	3,0·10⁶					1,06·10³	7,5·10²	1,8·10²	1,25·10²	1,11·10²
35						400	2,00	2,0·10⁷					1,62·10³	9,3·10²	1,2·10²	1,55·10²	1,0·10²
36	11	5. V/1956	7	04	1000	250	1,35	6,6·10⁵	5	0,7		III	1,67·10³	1,3·10³	1,4·10²	2,01·10²	1,48·10²
37						300	1,55	3,1·10⁶					1,59·10³	9,8·10²	1,8·10²	2,01·10²	1,29·10²
38						350	1,80	1,3·10⁷					1,40·10³	9,0·10²	1,4·10²	2,31·10²	1,11·10²
39	12	10. V/1956	9	41	1000	500	2,40	6,7·10⁵	6				8,4·10³	4,1·10³	1,2·10²	1,31·10²	1,0·10²
40						550	2,65	5,8·10⁶					7,2·10³	5,0·10²	8,5·10¹	9,62·10²	9,1·10²
41	13	15. V/1956	11	26	8000	400	2,00		5				1,86·10³	5,0·10²	2,3·10²	2,3·10²	2,00·10²
42						450	2,20						1,76·10³	6,0·10²	2,3·10²	1,70·10²	1,82·10²
43						500	2,40						1,77·10³	9,0·10²	1,8·10²	1,51·10²	1,67·10²
44	14	16. V/1956	8	36	7000	500	2,40		6				1,40·10³	2,4·10³	1,6·10²	2,3·10²	1,75·10²
45	15	20. VI/1957	18	02	4000	225	0,86	7,8·10⁵	10	0,8	1,4	IV	4,10·10³	6,0·10²	—	6,2·10²	4,6·10²
46						250	0,98	3,2·10⁶					4,20·10³	2,3·10²	—	7,3·10²	4,1·10²

Table 7 (Continued)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
47	15	20. IX/1957	18	02	1000	25	1,10	$2,0 \cdot 10^{9}$	10	0,8	1,4	IV	$3,81 \cdot 10^{3}$	$3,0 \cdot 10^{3}$	—	$6,0 \cdot 10^{3}$	$3,6 \cdot 10^{4}$
48	16	02. VII/1957	11	55	3000	150	0,50	$6,6 \cdot 10^{9}$	9	0,6	1,0	III	$6,70 \cdot 10^{3}$	$5,0 \cdot 10^{3}$	$1,4 \cdot 10^{3}$	$1,28 \cdot 10^{4}$	$9,0 \cdot 10^{4}$
49						175	0,62	$1,4 \cdot 10^{10}$					$6,50 \cdot 10^{3}$	$1,4 \cdot 10^{3}$	$1,6 \cdot 10^{3}$	$1,50 \cdot 10^{4}$	$7,3 \cdot 10^{4}$
50						200	0,74	$6,2 \cdot 10^{9}$					$6,50 \cdot 10^{3}$	$1,0 \cdot 10^{3}$	$1,3 \cdot 10^{3}$	$1,58 \cdot 10^{4}$	$6,1 \cdot 10^{4}$
51	17	15. VII/1957	10	50	2000	75	0,15	$2,1 \cdot 10^{10}$	9	0,8	1,4	II	$8,20 \cdot 10^{3}$	$5,0 \cdot 10^{3}$	$3,7 \cdot 10^{3}$	$2,10 \cdot 10^{4}$	$12 \cdot 10^{4}$
52						100	0,25	$8,7 \cdot 10^{9}$					$5,40 \cdot 10^{3}$	$3,6 \cdot 10^{3}$	$1,5 \cdot 10^{3}$	$1,73 \cdot 10^{4}$	$7,2 \cdot 10^{4}$
53						125	0,37	$2,9 \cdot 10^{10}$					$4,70 \cdot 10^{3}$	$2,0 \cdot 10^{3}$	$2,1 \cdot 10^{3}$	$1,93 \cdot 10^{4}$	$4,9 \cdot 10^{4}$
54	18	26. VII/1957	9	44	2000	75	0,15	$9,0 \cdot 10^{9}$	10	0,6	0,2	III	$7,70 \cdot 10^{3}$	$3,0 \cdot 10^{3}$	—	$2,0 \cdot 10^{4}$	$13,3 \cdot 10^{4}$
55						90	0,22	$6,7 \cdot 10^{9}$					$6,70 \cdot 10^{3}$	$1,6 \cdot 10^{3}$	—	$1,25 \cdot 10^{4}$	$9,1 \cdot 10^{4}$
56						105	0,27	$2,8 \cdot 10^{10}$					$7,0 \cdot 10^{3}$	$8,0 \cdot 10^{3}$	—	$1,28 \cdot 10^{4}$	$7,4 \cdot 10^{4}$
57	19	15. VIII. 1957	12	43	2000	10–60	0,07	$1,2 \cdot 10^{10}$	2	0,8	1,7	II	$2,40 \cdot 10^{3}$	$2,1 \cdot 10^{3}$	$1,2 \cdot 10^{3}$	$4,8 \cdot 10^{3}$	$5,7 \cdot 10^{4}$
58	20	22. VIII 1957	10	49	2000	10–60	0,07	$2,0 \cdot 10^{9}$	6	0,6	1,0	III	$3,20 \cdot 10^{3}$	$1,5 \cdot 10^{3}$	$1,6 \cdot 10^{3}$	$5,[illegible] \cdot 10^{3}$	$17,1 \cdot 10^{4}$
59	21	11. X/1958	3	20	150	15–65	0,12	$5,2 \cdot 10^{10}$	6				$1,5 \cdot 10^{3}$	$4,2 \cdot 10^{3}$	$1,2 \cdot 10^{3}$	$9,0 \cdot 10^{3}$	$6,67 \cdot 10^{4}$
60	22	22. IX/1959	10	25	1600	10–65	0,07	$6,6 \cdot 10^{9}$	4				$1,70 \cdot 10^{3}$	$2,1 \cdot 10^{3}$	$1,8 \cdot 10^{3}$	$7,8 \cdot 10^{3}$	$5,7 \cdot 10^{4}$
61	23	6. X/1959	10	28	1000	45–65	0,12	$5,2 \cdot 10^{10}$	8	1,0	1,7	I	$2,60 \cdot 10^{3}$	$1,3 \cdot 10^{3}$	$1,0 \cdot 10^{3}$	$1,15 \cdot 10^{4}$	$6,7 \cdot 10^{4}$
62	24	9. X/1959	11	01	2000	45–65	0,12	$5,2 \cdot 10^{10}$	4	0,8	0,9	IV	$3,11 \cdot 10^{3}$	$3,4 \cdot 10^{3}$	$1,8 \cdot 10^{3}$	$1,32 \cdot 10^{4}$	$6,67 \cdot 10^{4}$
63	25	9. X/1959	17	20	1000	10–45	0,07	$3,6 \cdot 10^{9}$	5				$3,22 \cdot 10^{3}$	$1,05 \cdot 10^{3}$	$1,7 \cdot 10^{3}$	$8,4 \cdot 10^{3}$	$7,14 \cdot 10^{4}$
64	26	11. X/1959	15	37	1000	45–65	0,12	$7,7 \cdot 10^{10}$	8	1,1	1,1	I	$4,0 \cdot 10^{3}$	$1,6 \cdot 10^{3}$	$1,4 \cdot 10^{3}$	$6,8 \cdot 10^{3}$	$6,7 \cdot 10^{4}$
65	27	23. X. 1959	13	05	300	80–100	0,22	$1,2 \cdot 10^{11}$	7	0,4	0,4	III	$2,5 \cdot 10^{3}$	$7,7 \cdot 10^{3}$	$1,2 \cdot 10^{3}$	$2,4 \cdot 10^{3}$	$9,6 \cdot 10^{4}$

Table 7 (Continued)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
66	28	31. V/1960	12	55	500	45—65	0,12	$5,1\cdot10^{11}$	7	0,9	0,9	III	$2,05\cdot10^{4}$	$1,7\cdot10^{3}$	$1,3\cdot10^{3}$	$8,4\cdot10^{3}$	$2,92\cdot10^{4}$
67	29	2. VI/1960	12	48	1000	10—45	0,07	$2,1\cdot10^{12}$	7	1,1	1,2	I	$1,5\cdot10^{4}$	$1,5\cdot10^{3}$	$1,7\cdot10^{3}$	$5,2\cdot10^{3}$	$10\cdot10^{4}$
68	30	3. VI/1960	12	50	500	45—65	0,12	$5,3\cdot10^{11}$	5	1,1	1,4	I	$1,40\cdot10^{4}$	$1,7\cdot10^{3}$	$1,2\cdot10^{3}$	$5,6\cdot10^{3}$	$2,1\cdot10^{4}$
69	31	7. VI/1960	12	30	1000	10—45	0,07	$1,9\cdot10^{12}$	2	1,0	1,1	II	$2,25\cdot10^{4}$	$8,4\cdot10^{3}$	$2,7\cdot10^{3}$	$6,2\cdot10^{3}$	$2,86\cdot10^{4}$
70	32	9. VI/1960	13	19	500	45—65	0,12	$1,0\cdot10^{12}$	7	1,5	1,5	I	$2,10\cdot10^{4}$	$1,2\cdot10^{4}$	$1,5\cdot10^{3}$	$7,4\cdot10^{3}$	$2,9\cdot10^{4}$
71	33	13. VI/1960	4	30	1000	10—45	0,07	$2,0\cdot10^{12}$	5				$3,70\cdot10^{4}$	$1,0\cdot10^{3}$	$1,1\cdot10^{3}$	$9,0\cdot10^{3}$	$7,1\cdot10^{4}$
72	34	15. VI/1960	10	43	1000	10—45	0,07	$2,0\cdot10^{12}$	2				$1,30\cdot10^{4}$	$5,2\cdot10^{3}$	$1,1\cdot10^{3}$	$5,2\cdot10^{3}$	$2,9\cdot10^{4}$
73	35	4. IX/1960	12	26	1000	10—45	0,07	$2,00\cdot10^{12}$	5	1,2	2,7	I	$2,75\cdot10^{4}$	$2,3\cdot10^{3}$	$1,2\cdot10^{3}$	$1,22\cdot10^{4}$	$7,14\cdot10^{4}$
74	36	5. IX/1960	12	13	1000	10—45	0,07	$2,0\cdot10^{12}$	6	1,1	1,3	I	$2,14\cdot10^{4}$	$2,7\cdot10^{3}$	$1\cdot10^{3}$	$8,2\cdot10^{3}$	$8,57\cdot10^{4}$
75	37	6. IX/1960	12	08	1000	45—65	0,12	$7,3\cdot10^{11}$	4,5	1,0	0,8	III	$3,20\cdot10^{4}$	$1,5\cdot10^{3}$	$1,8\cdot10^{3}$	$9,1\cdot10^{3}$	$3,8\cdot10^{4}$
76	38	7. IX/1960	12	09	1000	10—45	0,07	$2,0\cdot10^{12}$	7	0,9	1,6	IV	$3,0\cdot10^{4}$	$4,8\cdot10^{3}$	$1,8\cdot10^{3}$	$1,50\cdot10^{4}$	$10\cdot10^{4}$
77	39	9. IX/1960	12	15	1000	10—45	0,07	$4,3\cdot10^{12}$	5	1,2	3,0	I	$3,0\cdot10^{4}$	$4,0\cdot10^{3}$	$1,4\cdot10^{3}$	$8,1\cdot10^{3}$	$7,1\cdot10^{4}$
78	40	10. IX/1960	13	37	1000	45—65	0,12	$8,6\cdot10^{11}$	5	1,0	2,4	II	$2,94\cdot10^{4}$	$3,2\cdot10^{3}$	$1,8\cdot10^{3}$	$6,1\cdot10^{3}$	$4,17\cdot10^{4}$
79	41	11. IX/1960	13	30	1500	65—80	0,175	$8,0\cdot10^{11}$	4	1,0	1,0	I	$2,90\cdot10^{4}$	$1,2\cdot10^{3}$	$2,8\cdot10^{3}$	$7,4\cdot10^{3}$	$3,4\cdot10^{4}$
80	42	12. IX/1960	12	06	1000	65—80	0,175	$5,0\cdot10^{11}$	5				$2,42\cdot10^{4}$	$4,2\cdot10^{3}$	$1,2\cdot10^{3}$	$7,2\cdot10^{3}$	$2,86\cdot10^{4}$
81	43	12. IX/1960	15	09	1000	65—80	0,175	$1,8\cdot10^{11}$	2	1,1	1,8	I	$6,0\cdot10^{3}$	$5,5\cdot10^{3}$	$1,4\cdot10^{3}$	$7,7\cdot10^{3}$	$11,4\cdot10^{3}$
82	44	14. IX/1960	15	00	1000	65—80	0,175	$4,7\cdot10^{11}$	5	1,1	2,1	I	$2,70\cdot10^{4}$	$1,3\cdot10^{3}$	$1,5\cdot10^{3}$	$7,9\cdot10^{3}$	$2,9\cdot10^{4}$

The vertical profile of the wind vector was in most cases uniform without any sharply expressed fluctuations. Fluctuations of wind direction and velocity in one direction or another throughout the entire layer of particle spreading were within the limits of 10-20° and 1-2 m/sec. Average values of wind velocity during the experiments are presented in composite Table 7. As the data of the table indicate, the experiments were conducted in a wind of 2-15 m/sec. Cases of slight wind ($u < 2$ m/sec) were excluded from further consideration.

We know that the temperature stratification of the atmosphere is one of the important characteristics which permit determination of the degree of atmospheric stability. The results of aircraft sounding indicated that the atmosphere at altitude was stratified uniformly in all cases, except experiments 10, 15, 24 and 38, and the gradient over the entire altitude does not change sign. Average vertical temperature gradients γ in the layer of vertical settling calculated by temperature profile are given in Table 7. In cases of inversion gradient γ was calculated in the layer below the inversion (experiments 15, 24 and 38) and above the inversion layer in experiment 10. Graph 11 of this same table shows the temperature gradients in the lower 100 meters of the atmosphere (γ_{100}), where temperature stratification is more sharply expressed.

Analysis of temperature profiles permitted isolation of three main types of stratification of the atmosphere layer being considered which developed during the experiments.

Type I - energy of instability as positive throughout the entire layer being considered (vertical temperature gradient γ in the lower part of the layer is greater than 1°/100 m, and the superadiabatic or approximately equal gradients are higher).

Type II - in the lower section of the layer $\gamma > 1°/100$ m; here the instability energy is positive; higher $\gamma < 1°/100$ M, ~ 110, but there are no inversion and instability energy is negative.

Type III - instability energy over the entire layer is negative or equal to zero, temperature gradient is less than dry adiabatic or approximately equal to it, and there are no inversions.

Four cases with inversion are conditionally related to stratification Type IV. These cases are considered separately in Table 8, from which it is obvious that weak upper-air inversions were observed in three of them, and there was a rather strong inversion in the lower section of the boundary layer in one of them. The type of stratification for each experiment is indicated in Table 7.

Table 8

No. of Experiment	Altitude of lower inversion boundary, h (m)	Thickness of inversion layer Δh (m)	Temperature difference at upper and lower boundary of inversion layer Δt°
10	110	290	5.5
15	2800	220	0.8
24	1000	600	1.7
38	800	130	1.1

Analysis of experimental results. 82 experiments were conducted during the period from 1956 through 1960. The results are presented in composite Table 7. Initial data are also given here: H is the altitude of the source in meters; D is the mean diameter of the particles in microns; w is the velocity of gravitational settling of the particles in m/sec; Q is the quantity of particles at the source; u is the velocity of average wind in the layer of particle spreading in m/sec; γ is the mean vertical temperature gradient in the layer of particles settling in deg/100 m; γ_{100} is the vertical temperature gradient in the lower 100 meters of the atmosphere in deg/100 m.

The results of processing are also presented:
x_{max} is the distance from the projected release point to the maximum concentration found from the experiment, in meters*; q_{max} is the maximum surface concentration (particle/m^2) σ_y is the dispersion of the surface concentration of particles in a direction transverse to the wind from experimental data, in meters; σ_x is dispersion of the surface concentration of particles in a longitudinal direction from experimental data, in meters; x_{kine} is the coordinate of calculated kinematic maximum ($x_{kine} = \frac{uH}{w}$), in meters.

The first experiments on studies of particle dispersion were set up in 1955. They were set up to verify the developed methodology under field conditions. Particles of silica sand from 200-1000 microns and diameter were used in the experiments. The particles were released at various altitudes from 500 to 2000 meters. Figure 2 cites as an example

* In experiments with light particles x_{max} is the coordinate of the second (diffusion) maximum.

the track of fraction 250-400 microns obtained in the experiment of 16 August 1955. The drop was made from an altitude of 500 meters in a wind of 3-4 m/sec on a bearing of 111°. The atmosphere at altitude was stably stratified, and the vertical temperature gradient did not exceed 0.5°/100 m. The drop was made from an MI12 helicopter "suspended" in the air above the specified point. The figures in the diagram correspond to the values of the surface concentration of particles (the number of particles on an area of 1 m^2). The diagram shows isolines of concentration of 10^2, 10^3 and 10^5 part/m^2. As indicated by the diagram, alignment of the track axis (a line passing through the points of maximum concentration) agree well with the direction of average wind and the layer of particle settling. The track was fixed at a distance of 600 to 2100 meters from the projected drop point.

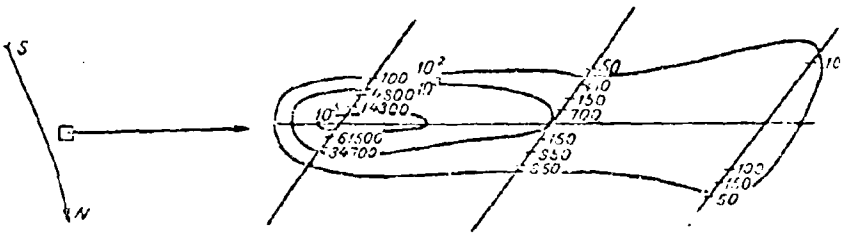

Figure 2
Isolines of surface concentration of particles in the experiment of 16 August 1955.

The 1955 experiments were tests and on their basis it became possible to conclude that the tested technique corresponds to the stated problem. Specific data obtained on the value of the basic parameters of the track which develops when particles 200-500 microns in diameter are dropped permitted further experiments to be set up more efficiently.

The experiments in 1956 were conducted from March to May in the region of the Golodnaya steppe of the Uzbek SSR. Particles of sand 200-600 microns in diameter were released from altitudes of 500-8000 meters. Results of the experiments are presented in Table 7. A description is given below of one of the typical experiments conducted on 21 April 1956 (experiment No. 6). Particle release was accomplished from an altitude of 1000 meters.

Table 9 shows the particle distribution by size at the source.

Table 9

Diameter, mu	175—225	225—275	275—325	325—375	375—425	425—475
No. of particles	$1,64 \cdot 10^5$	$11,7 \cdot 10^5$	$4,97 \cdot 10^5$	$6,5 \cdot 10^5$	$3,15 \cdot 10^5$	$1,09 \cdot 10^5$

Distribution of particle concentration at the surface is shown in Figure 3. The left of the track, bounded by a concentration isoline of 1000 part/m^2, which comprises 1/40 with respect to maximum concentration, is equal to 3 kilometers. After the sheets were processed under the microscope the tracks of the narrowest fractions were isolated - to 225-275, 275-325, 325-375, and 375-425 microns. Figures 4 and 5 show the typical distribution of service concentration along the x axis - in the direction of wind for sand particles 325-375 microns in diameter and in the direction lateral to the wind at the point of maximum concentration for particles of 225-275 microns.

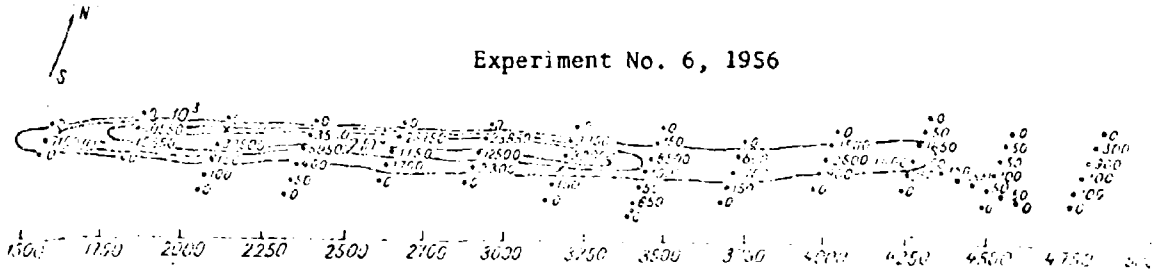

Figure 3
Isolines of surface concentration of particles in experiment 6 of 21 October 1956.

Experiments were set up for the first time in 1957 on dispersion of smaller particles from 10 to 300 microns in diameter from altitudes of 2000-5000 meters.

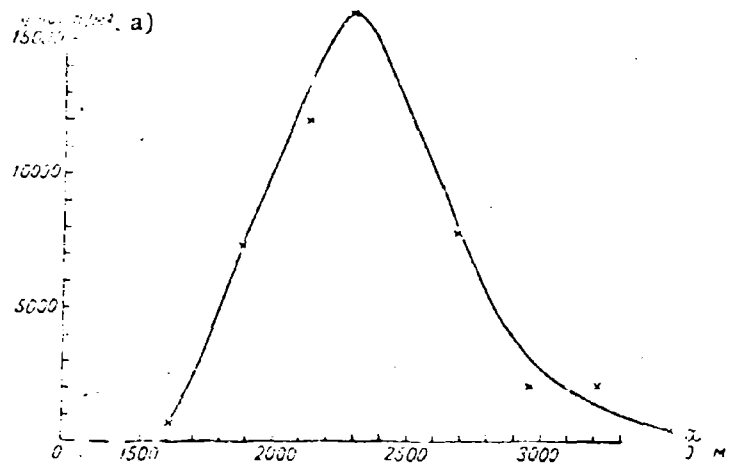

Figure 4
Distribution of surface concentration of sand particles (q) 325-375 microns in diameter along the x axis.
a) q,part/m^2

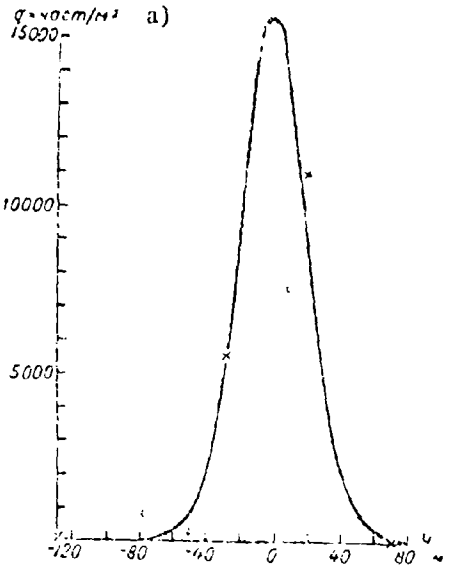

Figure 5
Distribution of service concentration (q) of sand particles 225-275 microns in diameter in the direction of the y axis at the point of maximum concentration.
a) q, part/m^2

In distinction from heavy particles, light particles disperse over wide areas. Thus, the track of light particles when dropped from an altitude of 1-5 kilometers have a length of several tens of kilometers and a width of 1-5 kilometers. A polygon approximately 6500 km^2 in area was laid out on the territory of the Moscow and Kaluga oblasts in order to capture such particles. The experiments were conducted from June through August. Results of the experiments are presented in Table 7. A description of experiment No. 16 which was conducted on 2 July is given below. The particles were released from an altitude of 5000 meters. Particle distribution by size at the source is given in Table 10.

Table 10

Diameter, mu	100±12,5	125±12,5	150±12,5	175±12,5	200±12,5	225±12,5
No. of particles (%)	2,9	5,4	22,0	47,3	20,6	1,8

The isoline with a concentration of 50 part/m^2 passes at a distance of 40 to 70 kilometers from the release point. The zone of maximum concentration bounded by an isoline of 200 part/m^2 is located at a distance of 63-67 kilometers from the projected release point. Maximum concentration comprises 250-270 part/m^2.

The 1959 experiments with light particles were conducted in the Dnepropetrovsk oblast, in an area 75 x 50 klm. Particles of 10 to 100 microns were dropped from altitudes of 300-2000 meters. The results of the experiments are given in Table 7.

The 1960 experiments with light particles were also carried out in the Dnepropetrovsk oblast during the period 23 May through 15 June and from 3 through 17 September. Particles 10-80 microns in diameter were released from altitudes of 500-1500 meters. A description of experiment No. 35 is given below. Outer particles 10-45 microns in diameter were released from an altitude of 1000 meters in an average wind of 5 m/sec.

Figure 6c and 6d show the distribution of surface concentration of particles along the x axis and in the direction of the y axis. As can be seen in the figure, two zones of increased concentration are apparent in the track. The first zone is an area approximately 4 klm^2 at a distance of 5-6 kilometers from the projected release point with maximum concentration of approximately 2300 particles on the area of the sheet (1200 cm^2). Concentration in the second zone is much less than in the first zone. The second zone is at a distance of 19-38 kilometers (the dimensions of the zone are bounded by a concentration isoline of 200 parts/1200 cm^2). The nature of these two maximums will be discussed below.

During the experiment visual observations of the motion of the visible part of the cloud were conducted from an aircraft. The cloud was observed to an altitude of 500 meters. The mechanical trajectory of this cloud is shown in Figure 6b.

Figure 7 depicts the distribution of surface concentration of particles of the same size in experiment No. 39. The figure indicates that the distribution pattern of surface concentration of particles is similar to experiment No. 35.

A review of the results of the experiments indicates that the distribution pattern of surface concentration presented in Figures 4 and 5 is representative for particles with a settling velocity greater than or equal to 1 m/sec. The maximum concentration of such particles is at a distance of $x_{max} = \frac{uH}{w}$, where u is the velocity of average wind in the layer of particles settling, H is the release altitude, and w is the velocity of particles settling.

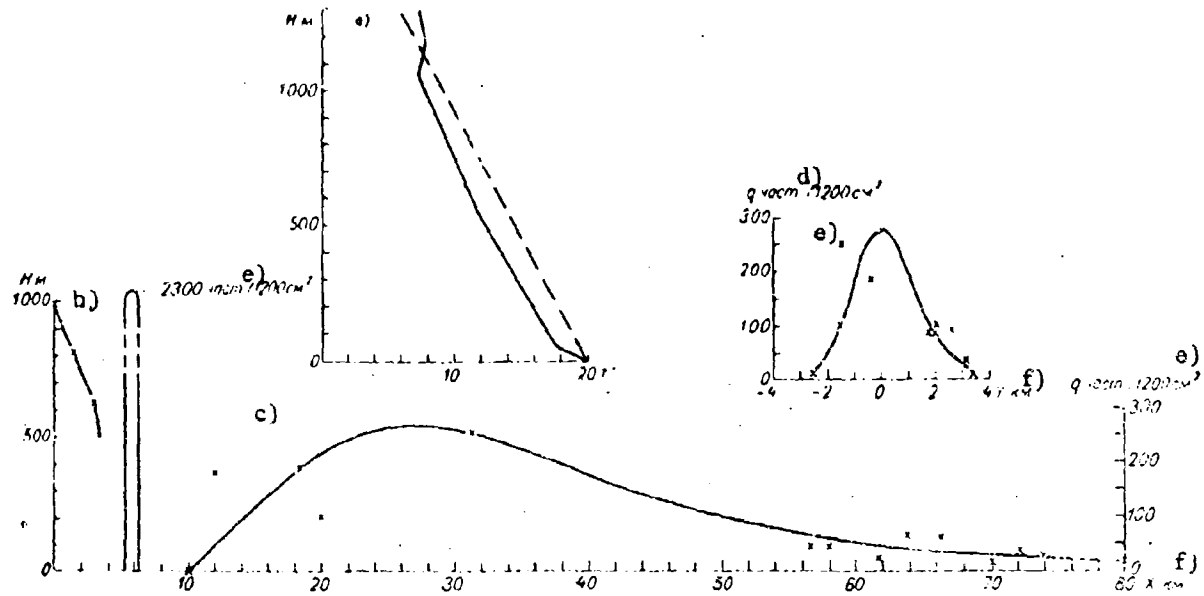

Figure 6

Experiment No. 35, 1960. a - temperature distribution (t°) of air at altitude (H) during the experiment (the dotted line denotes the dry adiabatic temperature gradient); b - mechanical trajectory of particle loud; c - distribution of the surface concentration (q) of particles along x axis; d - distribution of surface concentration (q) of particles along y axis; e - part/1200 cm^2; f - klm.

Figures 6 and 7 show the distribution of surface concentration of light particles 10-80 microns in diameter (w > 0.2 m/sec) released from an altitude of 1000 meters. It is obvious from the figures that an essentially different pattern is observed in this case. Two zones of increased concentration usually develop on the ground - the first at a distance of 6-12 kilometers and the second much farther off, but at a distance of x_{max}, which is in turn less than $x_{kine} = \frac{uH}{w}$. The surface concentration of particles in the region of the second zone is on the average an order less than that in the first zone. The area of the first zone is 4-9 klm^2 and the dimensions of the second zone are much greater.

The presence of a first maximum is explained by the characteristics of the particle source used, which at the moment of release forms a cloud of rather high concentration. Motion of this cloud, or rather of its

nucleus, has a single whole observed in a number of cases. It was possible to follow the moving cloud from an aircraft for 10-30 minutes depending on its color and the state of the atmosphere; these observations permitted calculation of the mean velocity of its motion. Comparison of the results of aircraft measurements with ground data (Figures 6b and 7b) indicates that the first maximum is developed by the fall of this nucleus as a single whole. The vertical velocity of the nucleus exceeds by 3-5 times the stokes velocity of individual particles and it is not uniform in different experiments. More detailed information about this phenomenon is presented in paper [7].

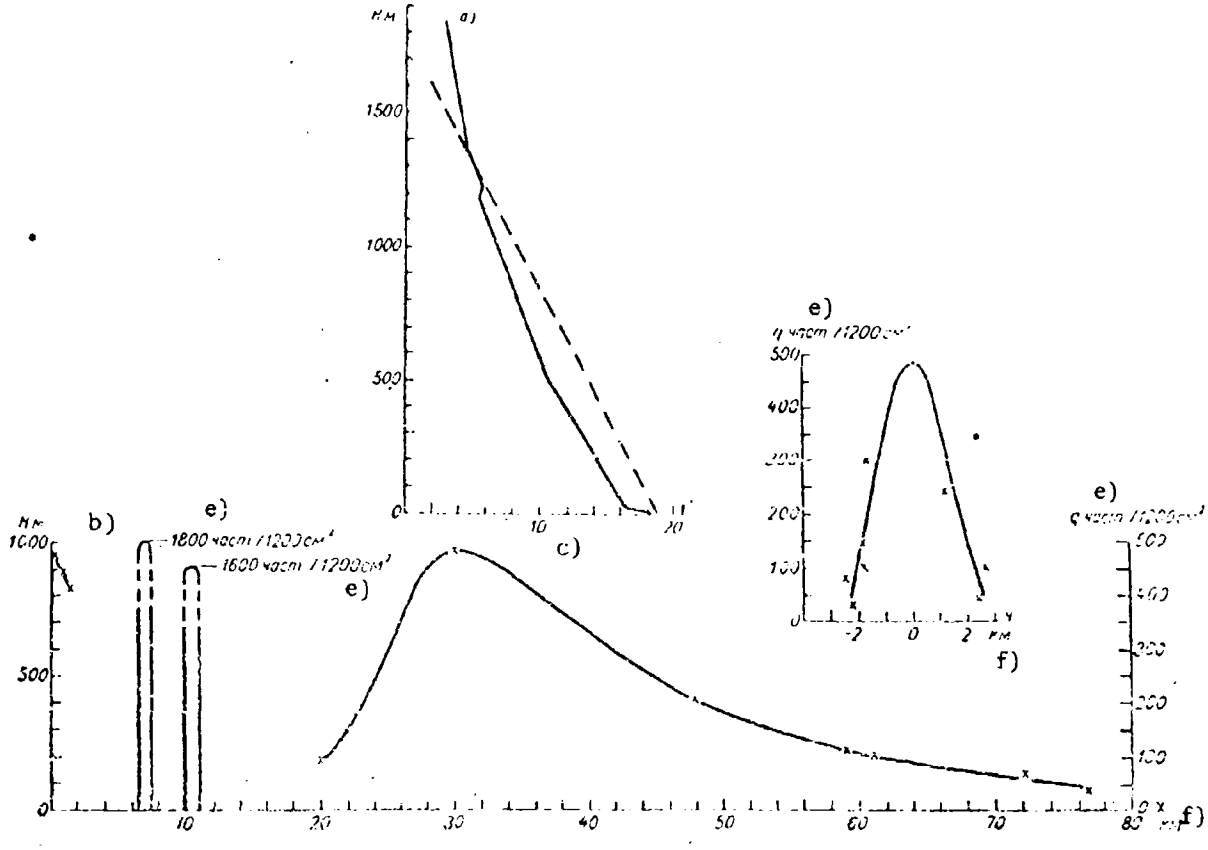

Figure 7

Experiment No. 39, 1960. a - temperature distribution (t°) of air at altitude (H) during the experiment (the dotted line denotes the dry adiabatic temperature gradient); b - mechanical trajectory of the particle cloud; c - distribution of surface concentration (q) of particles along x axis; d - distribution of surface concentration (q) of particles along y axis; e - part /1200 cm²; x - klm.

According to very approximate calculations, approximately 1/10 of the total number of particles in the cloud is contained in the portion of particles in the nucleus. The main cloud mass having a very low density disperses due to the effect of atmosphere turbulence and develops a second diffusion maximum of concentration on the ground, according to the descent velocities of individual particles. The track pattern on the surface is usually somewhat irregular, spotty as it were. This spottiness is determined by a number of circumstances. Besides the purely statistical error related to the number of particles on the sheet and calculated by Poisson's law, a role is played by a certain irregularity of the underlying surface (microrelief, diverse vegetation, etc.), by the unaccounted for characteristics of the position of the sheet, and by the effect of wind variability. These circumstances are more evident during dispersion of light particles settling over a wide area than that of heavy particles.

The track of heavy particles is less spotty. Despite the spottiness, the position of the maximum is calculated precisely in all cases with an accuracy of approximately 10%, and the width of the track may be calculated with approximately the same accuracy. Determination of the maximum concentration of particles is somewhat worse. However, statistical reliability when calculating the concentration in an area of the maximum, where 200-500 particles are observed on the sheet, is satisfactory even here and the concentration is determined with an error of approximately 50% on the average.

Empirical-formula Dependencies

As indicated above, the dispersion pattern of an admixture in the atmosphere is presented from a qualitative aspect in the following manner - the admixture is carried in the direction of the wind and settles due to the force of gravity - the effect of atmosphere turbulence which leads to dispersion of the admixture is applied to these motions. The problem consists in describing this process in numerical form. On the whole this problem is rather complex. The state of the theory does not permit consideration of the diversity of factors causing dispersion, and these factors themselves may not always be accurately measured in the free atmosphere.

The theoretical approach to the problem of atmosphere diffusion is outlined in papers [6, 8]. We shall only point out briefly here that the overall complexity of practical use of the equation for turbulent diffusion, which is usually used to describe this process, consists of the fact that first of all the dependence of the turbulent scattering factors making up this equation on the parameters which determine them are inadequately known, because the entire mechanism of complex interactions which characterize the physical processes of turbulent mixing in the free atmosphere are insufficiently known. For this reason turbulent dispersion factors are calculated either on the basis of certain hypotheses or by experiment. Moreover, the equation for turbulent scattering itself may be solved analytically only

on certain assumptions, which are not always strictly valid for the real process. Solutions of the turbulent dispersion equation for an admixture released into the free atmosphere are given for certain special cases, for example, in papers [3, 10, 11 and 12].

It is obvious from the foregoing that it is not yet possible to utilize the theory of turbulent diffusion to interpret the results obtained. However, solution of many applied problems requires development of simple, even approximate methods of calculating the dispersion of various types of admixtures in the atmosphere. Therefore, we feel it is feasible and very important to derive simple empirical formulas to calculate the surface concentration of an admixture which is being dispersed in the free atmosphere from high-altitude sources.

An attempt to determine the turbulent dispersion coefficients of an admixture in the equation solved on the assumption that these coefficients are constant is made in the following chapter. Here we dwell on consideration of empirical-formula dependencies and state the problem of calculating basic parameters of the track of falling particles as a function of initial data of the experiment - release altitude (H), settling velocity of the particles (w), velocity of average wind (u) and number of particles at the source (Q). The initial material for the given goal are the results of experiments presented in Table 7. The experiments include a wide range of settling velocities of particles from 0.07 to 3 m/sec and various altitudes (from 500 to 8000 meters).

Determining the position of maximum concentration of particles (x_{max}). If the particles were mixed only due to the effect of gravity and average wind, they would all fall at a distance $x_{max} = \frac{uH}{w}$ from the projected release point.

In the case of the real atmosphere, the effect of atmospheric turbulence, which leads to dispersion of the admixture, is reflected in this pattern. If the particles are large (their settling velocity is great), the determining factor in their dispersion is gravitational settling, and the effect of turbulence is comparatively small. As particle size diminishes during dispersion, constantly acting atmospheric turbulence begins to be involved in addition to gravitational forces. Gravitational settling assumes ever less significance, and the role of turbulent scattering increases, in proportion to the decrease in particle size. And, finally, in the case of the smallest particles which may be considered as an almost weightless admixture, the effect of atmospheric turbulence completely dominates gravitational settling. The intensity of the turbulence is determined by the wind field and by the degree of thermal stability of the atmosphere, and it is quite natural that strong winds and unstable stratification contribute to an increase in turbulent dispersion. Thus, the value of x_{max} is actually dependent on the gravitational settling velocity of particles, wind velocity, release altitude and the thermal state of the atmosphere.

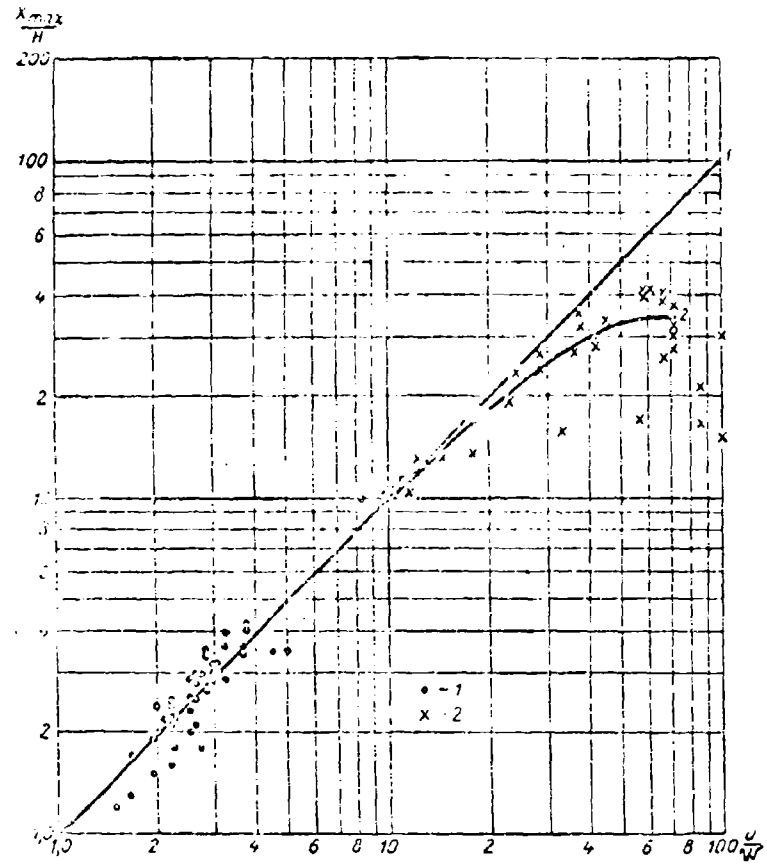

Figure 8

Dependence of $\frac{x_{max}}{H}$ on $\frac{u}{w}$. 1 - experimental data corresponding to settling velocity of particles from 2.7 to 1 m/sec and average wind velocity from 3 to 15 m/sec; 2 - experimental data with settling velocities of $w < 1$ m/sec. (straight line (1) denotes the variation in the value of kinematic maximum and curve (2) was plotted from experimental data).

Figure 8 shows the dependence of the dimensionless ratio $\frac{x_{max}}{H}$ on the value of the ratio $\frac{u}{w}$, which determines the relation of wind velocity and gravitational settling velocity of particles. The dots represent experimental data corresponding to values of w from 2.7 to 1 m/sec, and the crosses represent values of $w < 1$ m/sec. Straight line 1 denotes the variation in the value of the kinematic maximum and curve 2 is the mean line passing through the experimental points. As the figure indicates, the extent of the

effect of atmospheric turbulence during particle dispersion is characterized by the ratio $\frac{u}{w}$. Thus, when $\frac{u}{w} < 10$ the kinematic method of determining x_{max} where 10 is valid. Vertical turbulent mixing of the atmosphere, the effect of which shifts the maximum of surface concentration toward the source ($x_{max} < x_{kine}$), begins to have an apparent effect on particle dispersion. The determining factor in particle dispersion when the value $\frac{u}{w} > 60$ is apparently atmospheric turbulence. In this case the value of x_{max} comprises approximately 30 to 40% of release altitudes for conditions close to equilibrium and slightly unstable stratification of the atmosphere. As temperature and stability increase in similar conditions, the effect of turbulence will appear at a smaller value of $\frac{u}{w}$ and the value of x_{max} will decrease.

The dependence of $\frac{x_{max}}{x_{kine}}$ on $\frac{u^2}{w^2}$ is given in Figure 9, which indicates that its empirical formula for the range of w from 0.07 to 3 m/sec may be adequately written in the form

$$\frac{x_{max}}{x_{kine}} = \sqrt{\left(\mu \frac{u^2}{w^2}\right)^2 + 1} - \mu \frac{u^2}{w^2}, \qquad (1)$$

where μ is a certain dimensionless parameter apparently related to the thermal stability of the atmosphere. The values of the parameter of μ calculated for a number of experiments where H = 1000 meters are given in Table 11. The line in Figure 9 is th calculated curve from formula (1) at a value of $\mu = 1.5 \cdot 10^{-2}$

The spread of the values of μ presented in the table is explained by the differences in the thermal state of the atmosphere, and also by the error in measuring the parameters of x_{max}, u and H. The inadequate number of experiments did not permit obtaining a precise dependence of the parameter of μ on atmospheric stratification. However, it may be pointed out that the value of μ increases as the rate of instability increases.

Dispersion distribution of surface concentration of particles in the direction of and transverse to the wind. We know that distribution of the surface concentration of particles in a direction transverse to the wind is subject to the Gauss law [13] and at $x = x_{max}$ has the form

$$q = q_0 e^{-\frac{y^2}{2\sigma_y^2}}.$$

Table 11

Track No.	u	ω	μ	Stratification of atmosphere
67	7	0,07	$3,3 \cdot 10^{-4}$	Unstable
74	6	0,07	$2,5 \cdot 10^{-4}$	"
73	5	0,07	$2,2 \cdot 10^{-4}$	"
77	5	0,07	$1,9 \cdot 10^{-4}$	"
63	5	0,07	$1,8 \cdot 10^{-4}$	
76	7	0,07	$1,5 \cdot 10^{-4}$	Unstable in lower part, stable with inversion higher up
71	5	0,07	$1,5 \cdot 10^{-4}$	
61	8	0,12	$2,4 \cdot 10^{-4}$	Unstable
78	5	0,12	$1,9 \cdot 10^{-4}$	Unstable in lower part of layer, stable higher up
64	8	0,12	$1,2 \cdot 10^{-4}$	Unstable
75	4–5	0,12	$1,1 \cdot 10^{-4}$	Stable

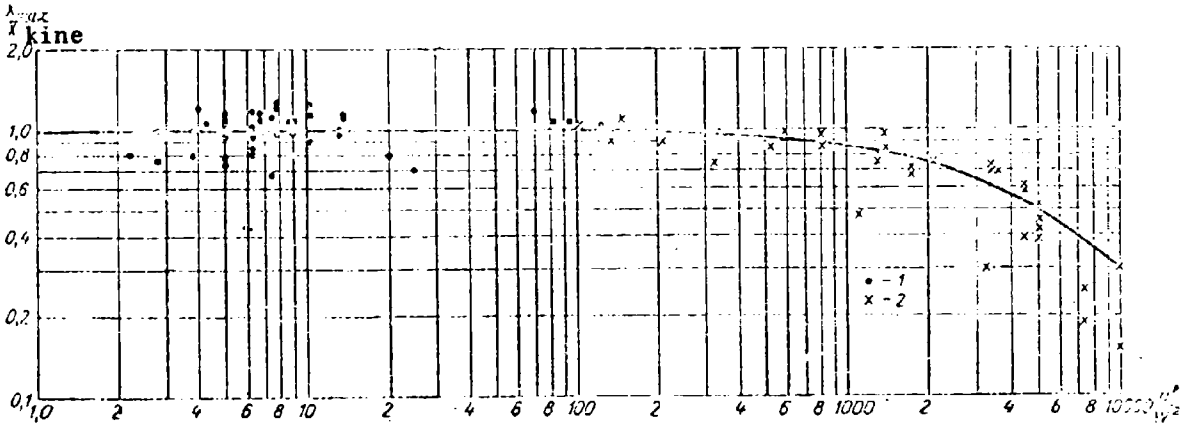

Figure 9

Dependence of $\frac{x_{max}}{x_{kine}}$ on $\frac{u^2}{w^2}$. 1 - experimental data for particles with settling velocities of $w \geq 1$ m/sec; 2 - experimental data at settling velocities of 1 m/sec. The solid line represents the calculated curve from formula (1) at the value $\mu = 1.5 \cdot 10^{-4}$; a) $\frac{x_{max}}{x_{kine}}$.

This dispersion distribution σ^2_y permits calculating the width of the track of the falling particles in the zone of maximum concentration.

Inasmuch as the dispersion rate depends on the time the particles are located in the atmosphere and on wind velocity, the value of dispersion should increase as distance from the source increases. The dependence dence of the value of σ^2_y on distance x_{max} is given in Figure 10. It is quite obvious here that this dependence, in both cases close to a linear dependence, is different for small particles ($w \leq 0.2$ m/sec) and for large particles ($w \leq 1$ m/sec); the track of large particles on the average is much narrower Thus, we may assume approximately that

$$\sigma_y = b_y x_{max}, \qquad (2)$$

where b_y is the dimensionless coefficient related to the variability of wind direction. The mean value of b_y for light particles is $6.2 \cdot 10^{-2}$ and for heavy ones $1.1 \cdot 10^{-2}$; the standard deviation is $2.6 \cdot 10^{-2}$ and $0.3 \cdot 10^{-2}$ respectively. Figure 11 shows the dependence of σ_y on the dimensionless parameter of $\frac{u}{w}$. This dependence over the entire range of w may be represented as an average of the formula

$$\sigma_y = a_y H \left(\frac{u}{w}\right)^n \qquad (3)$$

where n = 1.3 and $a_y = 8 \cdot 10^{-3}$.

In distinction from a distribution of particle concentration transverse to the wind, which is determined only by the variability of wind direction, distribution along the x axis depends on a number of factors - variability of the longutinal component of wind velocity, on the nature of vertical dispersion, and on the degree of polydispersion of particles forming the track.

As Figures (4, 6 and 7) indicate, distribution of the surface concentration of the heavy particles is somewhat asymmetrical, and it is more elongated in the zone behind the maximum than it is in front of it. This asymmetry is greater for light particles.

The value of σ_x was assumed as the characteristic of track length, and was determined by formula

$$\sigma_x = \frac{x_1 - x_2}{3},$$

where l_1 is the width of the distribution of surface concentration along x axis at a level of $\frac{q}{q_{max}} = 0.6$ and l_2 is the width of distribution of surface concentration along x axis at level $\frac{q}{q_{max}} = 0.1$.

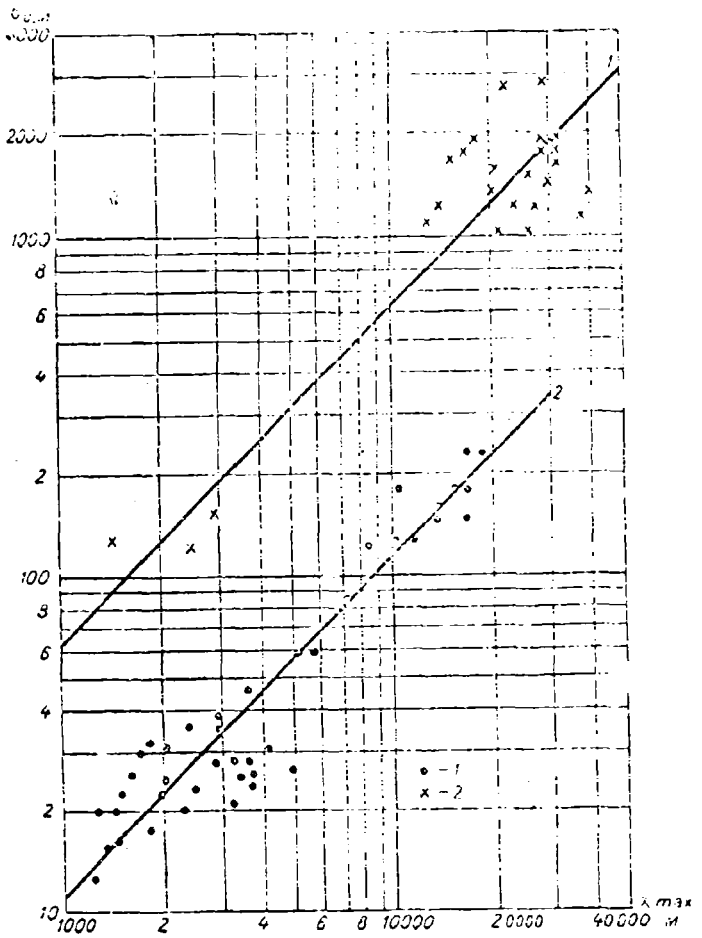

Figure 10

Dependence of σ_y on x_{max}; 1 - experimental data corresponding to particles settling velocities of $w \geq 1$ m/sec; 2 - experimental data corresponding to particles settling velocities of $w \geq 0.2$ m/sec.

Dependence of the value of $\frac{\sigma_x}{H}$ on $\frac{u}{w}$ for this range of w is given in Figure 12. This dependence may be written as an average by the empirical

formula of the type

$$\sigma_x = a_x H \left(\frac{u}{w}\right)^n, \tag{4}$$

where n = 1.15 and $a_x = 1.0 \cdot 10^{-1}$.

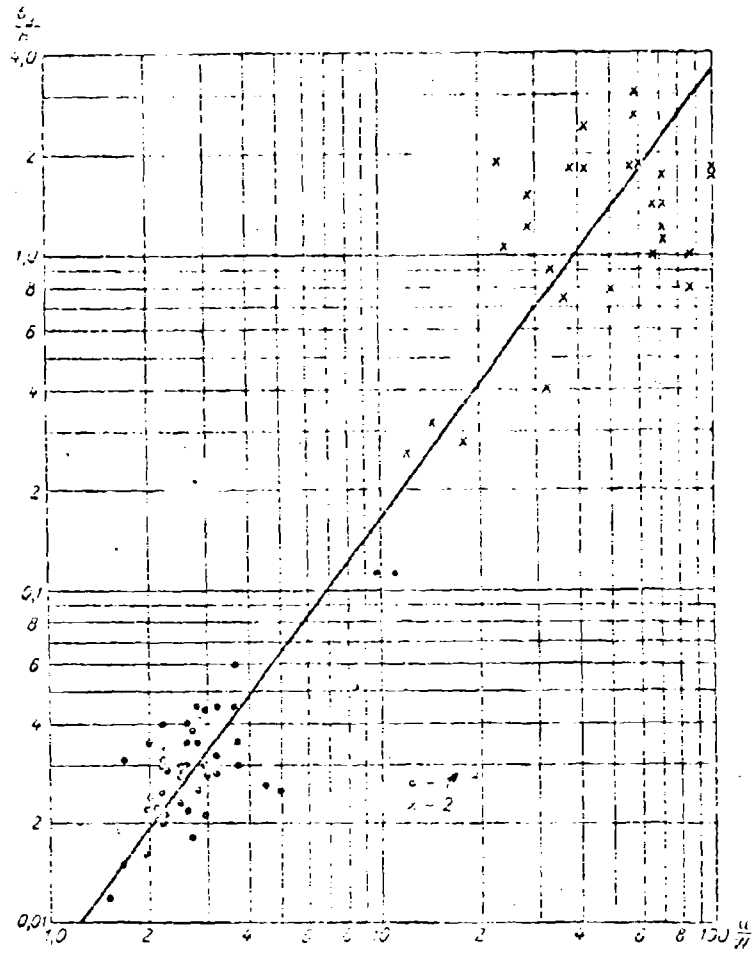

Figure 11

Dependence of $\frac{\sigma_y}{H}$ on $\frac{u}{w}$. 1 - experimental data for particles with settling velocities of w > 1 m/sec; 2 - experimental data for particles with settling velocities of w ≥ 1 m/sec.

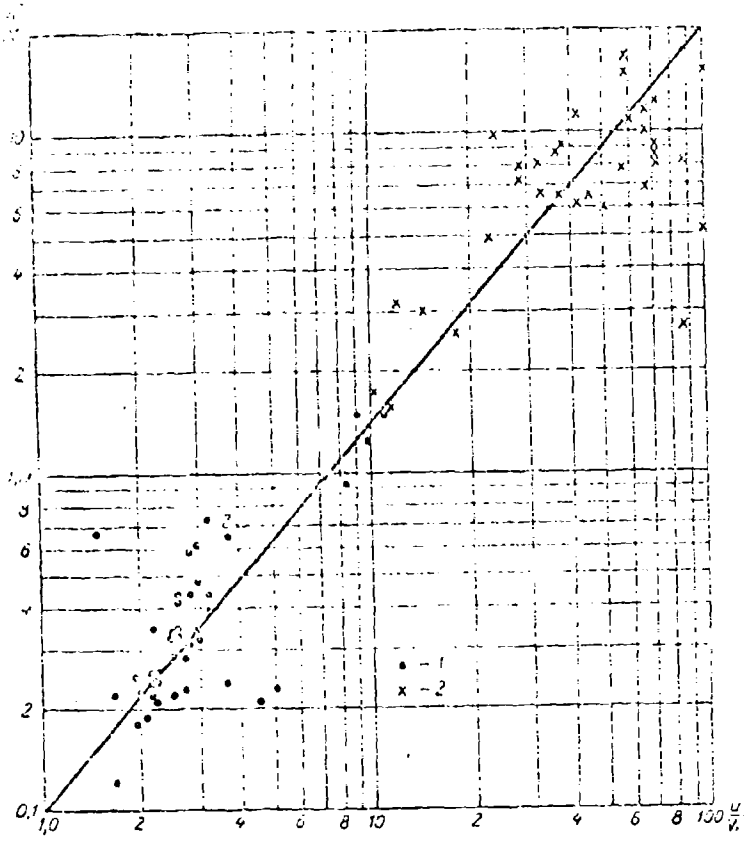

Figure 12

Dependence of $\frac{\sigma_x}{H}$ on $\frac{u}{w}$. 1 - experimental data for particles with settling velocities of $w \geq 1$ m/sec; 2 - experimental data for particles with settling velocities of $w < 1$ m/sec.

$\frac{1}{H}\sqrt{\frac{Q}{q_{max}}}$ от $\frac{u}{\omega}$

Surface concentration of particles at a distance of $x = x_{max}$.

Surface concentration of the admixture at a distance of x_{max} under given weather conditions is determined by the number of particles at the source, by wind velocity, release altitude and settling velocity of the particles in the atmosphere.

Dependence of the dimensionless value of $\frac{1}{H}\sqrt{\frac{Q}{q_{max}}}$ on $\frac{u}{w}$ for the entire range of w is shown in Figure 13. The spread of the points on the graph is rather large and is explained first of all by the fact that under real conditions numerous natural factors cause significant fluctuations in the distribution of the surface concentration, and the accuracy of the determination of the parameters which are taken into consideration is not high. However, despite the large spread, one may perceive a certain principle in the distribution of points on the graph which is satisfactorily explained by an empirical formula of the type

$$q_{max} = A\frac{Q}{H^2}\left(\frac{w}{u}\right)^{2n}[\text{part}_{xy}^{-2}], \qquad (5)$$

where n = 1.4 and the dimensionless parameter $A = 2 \cdot 10^2$.

We note in concluding the chapter that the empirical-formula dependencies obtained may be used to calculate the parameters of the track of an admixture released from an instantaneous point source according to given drop parameters (H, Q and w) and a mean wind velocity (u) in the particle distribution layer in the range of w from 0.07 m/sec to 3 m/sec. These dependencies permit calculation of maximum surface concentration and estimation of the dimensions of the contaminated zone by using expressions (1) - (5).

The mean values obtained for empirical dimensionless parameters of μ, A and b_y are suitable in the case of light particles ($0.175 \geq w \geq 0.07$) for a source altitude of approximately 1000 meters. Formulas (1) - (5) are valid for heavy particles up to an altitude of 8000 meters.

Estimating the Coefficients of Turbulent Particle Dispersion

Basic assumptions. In addition to the empirical-formula dependencies obtained in the preceding chapter, experimental data was used to calculate the coefficients of turbulent particle dispersion, for estimation of which was used the solution of the semi-empirical equation for turbulent diffusion

$$\frac{\partial q}{\partial t} + u\frac{\partial q}{\partial x} - w\frac{\partial q}{\partial z} = \frac{\partial}{\partial x}K_x\frac{\partial q}{\partial x} + \frac{\partial}{\partial y}K_y\frac{\partial q}{\partial y} + \frac{\partial}{\partial z}K_z\frac{\partial q}{\partial z}, \qquad (6)$$

where q is the volumetric concentration of particles, xy is the surface of the earth, z is the vertical axis, t is time, u is horizontal wind velocity, w is gravitational settling velocity of the particles, and K_x, K_y and K_z are the corresponding dispersion coefficients in three directions. Since the experimental results (distribution of surface concentration from a high-altitude source) are a certain total effect of diffusion over the entire dispersion layer from source altitude to the surface of the earth,

we may speak of estimating only the integral diffusion characteristics for the entire layer. Taking into account that the ground layer with a sharply defined vertical inhomogeneity is only a small fraction of the dispersion layer, we may assume the values of K_x, K_y and K_z to be independent of the coordinates, but we shall consider them parametrically dependent only on the values of u, H and w.

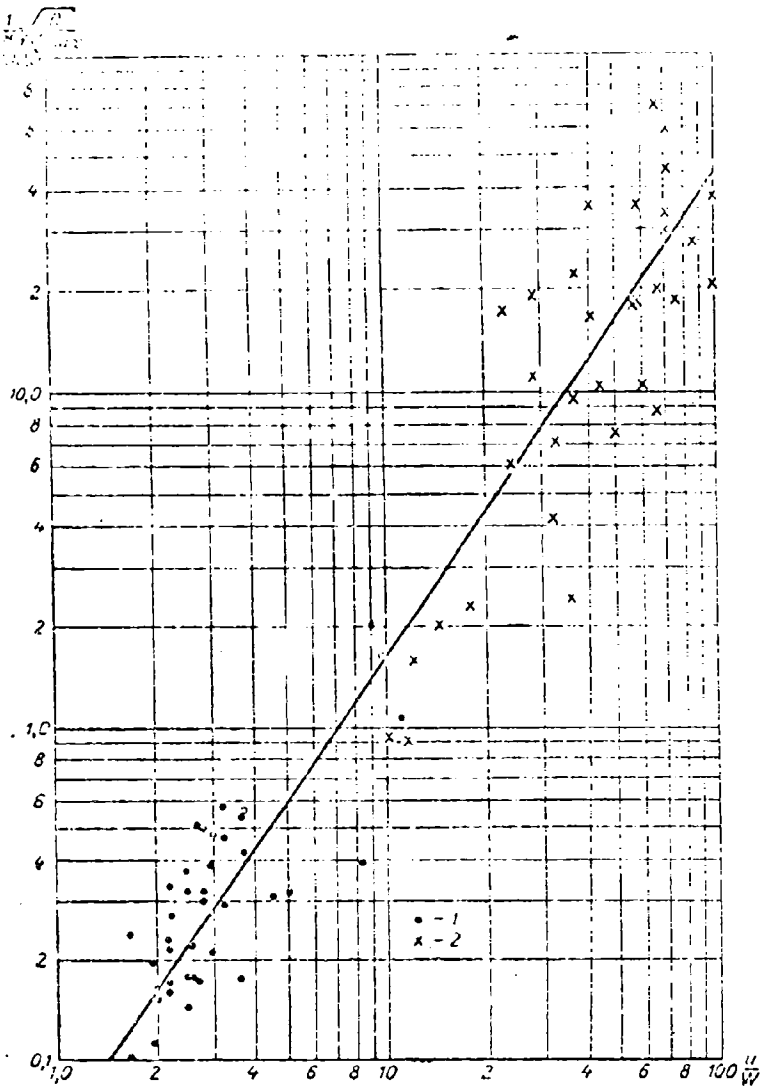

Figure 13

The initial condition is assumed to be the presence at the initial moment of an instantaneous source of capacity Q at altitude H at point x = y = 0, when t = 0 and $q = Q\delta(x)\delta(z-H)$.

The boundary condition, which at z = 0 and q = 0, expresses the condition of total absorption of the particles by the underlying surface. The second boundary condition at infinity has the form

$$q = 0 \text{ при } \sqrt{x^2 + y^2 + z^2} \to \infty.$$

In this case solution of equation (6) is written in the following form

$$q = \frac{Q}{8\pi^{3/2} t^{3/2} \sqrt{K_x K_y K_z}} \exp\left[-\frac{\omega^2 t}{4K_z} - \frac{\omega(z-H)}{2K_z} - \right.$$
$$\left. - \frac{(x-ut)^2}{4K_x t} - \frac{y^2}{4K_y t}\right] \times \left\{\exp\left[-\frac{(z-H)^2}{4K_z t}\right] - \exp\left[-\frac{(z+H)^2}{4K_z t}\right]\right\}. \quad (7)$$

Particle concentration at the surface on the track axis (y = 0) q_{surf} is determined by the expression

$$q_{surf} = \int_0^\infty K_z \left.\frac{\partial q}{\partial z}\right|_{z=0} dt = \frac{QH}{4\pi \sqrt{K_x K_y K_z}} \times$$
$$\times \frac{\sqrt{\frac{u^2}{K_x} + \frac{\omega^2}{K_z}}}{\frac{x^2}{K_x} + \frac{H^2}{K_z}} \left(1 + \frac{2}{\left(\frac{xu}{K_x} + \frac{H\omega}{K_z}\right)\sqrt{1+Y}}\right) \times \quad (8)$$
$$\times \exp\left[\frac{1}{2}\left(\frac{xu}{K_x} + \frac{H\omega}{K_z}\right)\left(1 - \sqrt{1-Y}\right)\right],$$

where

$$Y = \frac{(Hu - x\omega)^2}{K_z K_x \left(\frac{xu}{K_x} - \frac{\omega H}{K_z}\right)^2}$$

Expression (8) is particle distribution from the instantaneous point source along the surface (the track) and may be used to calculate diffusion coefficients when compared with experimental data.

Estimating the Coefficient of Vertical Diffusion K_z

The position of maximum concentration is calculated from (8) by condition $\frac{dq}{dx} = 0$. It is pointed out in paper [10] that this position does not depend on the coefficient of K_y and is determined by values of coefficients K_x and K_z. The paper also explained the conditions under which the main role belongs to the coefficient of K_z. Let us briefly review these results. In an extreme case, when $K_x \to \infty$, the expression to calculate the value of x_{max} has the form

$$\frac{x_{max}}{x_{kine}} = \frac{1 + 2\frac{K_z}{\omega H}}{12\frac{K_z}{\omega H} + 6\frac{K_z}{\omega H + 1}}. \qquad (9)$$

Other extreme cases yield: when $K_z \to 0$ vertical dispersion does not occur and

$$x_{max} \to x_{kine} \to \frac{uH}{w};$$

when $K_z \to \infty$ $x_{max} \to 0$.

In case of fulfillment of the conditions

$$\frac{K_x \omega^2}{K_z u^2} \ll 0{,}4; \quad \frac{x_{max}}{x_{kine}} \geq 0{,}4;$$
$$\frac{K_z}{\omega H} \ll 1,$$

as indicated in [10], expression (8) is simplified, assuming the form

$$q_{surf} = \frac{Q}{4\pi\sqrt{K_y K_z}} \frac{\omega^2}{uH} \frac{\sqrt{1 + \frac{\omega^2 K_z}{u^2 K_x}}}{\left(\frac{x_{max}}{x_{kine}}\right)^2 + \frac{\omega^2 K_y}{u^2 K_x}} \times$$

$$\times \exp\left[-\frac{\frac{\omega H}{K_z}\left(1 - \frac{x_{max}}{x_{kine}}\right)^2}{4\left(\frac{x_{max}}{x_{kine}} + \frac{\omega^2 K_y}{u^2 K_x}\right)}\right]. \qquad (10)$$

In this case, as calculations indicated, the value of x_{max} is dependent mainly on the coefficient of vertical dispersion of K_z. The simplest expression for calculating the value of x_{max} by the value of K_z is obtained when $K_x \to 0$; it has the form

$$\frac{x_{max}}{x_{kine}} = \frac{4K_z}{wH} + \sqrt{\left(\frac{4K_z}{wH}\right)^2 + 1}, \tag{11}$$

hence

$$K_z = wH \frac{1 - \left(\frac{x_{max}}{x_{kine}}\right)^2}{4\frac{x_{max}}{x_{kine}}}. \tag{12}$$

Calculations by formulas (11) and (9) yield almost identical results [10]; thus, the value of K_x over the entire possible range of variations has no apparent effect on the value of x_{max}.

The relationship between K_z and the empirical dimensionless parameter μ may be obtained by comparing formulas (1) and (11)

$$K_z = \frac{\mu}{2} \frac{u^2 H}{w}. \tag{13}$$

Table 12 gives the values of the parameter of μ, calculated for each track of light particles by the formula

$$\mu = \frac{1}{\frac{u^2}{w^2}} \cdot \frac{1 - \left(\frac{x_{max}}{x_{kine}}\right)^2}{2\frac{x_{max}}{x_{kine}}}, \tag{13a}$$

based on experimental data.

As indicated in Table 11 given above, the parameter of μ depends on the state of the atmosphere and has a greater value in the case of unstable stratification of the atmosphere. Table 12 also gives values of K_z calculated by formula (12).

When H < 500 meters, expression (12) may be used only in those cases when the real source models and instantaneous point source with sufficient accuracy. This condition is far from fulfilled in particular, in experiments described in this paper, when H < 500 meters, because of imperfection of the device dispensing the aerosol and because of such a high

concentration of the substance in the cloud at the initial moment, so that it is impossible not to consider this phenomenon in the calculation scheme. The case of particles settling from a "dusty" source, having a natural velocity of vertical motion, is considered in paper [9]. The position of extreme points of surface concentration and the velocity of vertical motion of the "dusty" source - the cloud of particles moving as a single unit with loss of material along the periphery - must be known in order to calculate K_z.

Table 12

Table of values of K_y and K_z for light spherical particles
(w = 0.07-0.175 m/sec; d = 1.1 g/cm^3)

Track No.	n	ω	$\beta_y \cdot 10^2$	K_y (exper.)	K	$\mu \cdot 10^4$	K_z
			H = 500 m				
68	5	0,12	0,37	257		2,4	6
65	7	0,12	0,20	288		1,1	6
70	7	0,12	0,25	375		0,98	5
			H = 1000 m				
60	4	0,07	0,50	381		4,7	27
75	4,5	0,12	0,16	227	8	1,2	5
63	5	0,07	0,14	224		1,7	16
71	5	0,07	0,09	82		1,4	11
73	5	0,07	0,10	131	35	2,2	19
77	5	0,07	0,11	161	15	1,9	17
78	5	0,12	0,19	275	20	2,0	11
80	5	0,175	0,12	149		2,0	7
82	5	0,175	0,15	208		0,92	3
74	6	0,07	0,11	140	39	2,6	33
67	7	0,07	0,61	674	45	3,5	57
76	7	0,07	0,18	378	20	1,5	27
61	8	0,12	0,07	154	58	2,5	53
64	8	0,12	0,05	196	7	1,2	16
			H = 1500 m				
79	4	0,175	0,47	541		3,2	11
			H = 2000 m				
62	4	0,12	0,16	205		7,5	25
58	6	0,07	0,12	233		3,5	89

For comparison with K_z Table 12 shows the coefficient of turbulence K calculated by V. L. Laykhtman's formula [4].

$$K = \frac{2l(\lg e)^2}{\left[\frac{d}{dz}\lg\left[(ug - u)^2 + (vg - v)^2\right]\right]^2},$$

where $l = 2\omega \sin\phi$ is the Coriolis parameter, e is the base of a natural logarithm, u and v are the components of the wind vector, u_g is the velocity of geostrophic wind. The formula permits determining the mean turbulence coefficient in the layer from 100 meters to the level of geostrophic wind. In some cases the nature of the variation in the wind profile with altitude did not permit calculation of the coefficient of K. As the data from the table indicate, mean values of K for the entire layer were obtained by those comparable to the coefficient of K_z.

Estimating the coefficient of transverse diffusion K_y. As follows from solving equation (6) in the case of $K_x = 0$, surface concentration along y is subject to the Gauss law, dispersion comprising

$$\sigma_y^2 = 2K_y \frac{x_{max}}{u}. \qquad (14)$$

Comparing this expression with empirical formula (2) for dispersion of the surface concentration at distance $x = x_{max}$, we obtain the relationship of the empirical parameter of b_y found earlier with the coefficient of K_y

$$K_y = \frac{b_y^2}{2} u x_{max}. \qquad (15)$$

Tables 12 and 13 show the values of $\beta_y = \frac{\sigma_y^2}{2}$, calculated for each track by the formula

$$\beta_y = \frac{1}{2} \cdot \frac{\sigma_{y\,max}^2}{x_{max}^2}, \qquad (16)$$

where σ_{ymax}^2 is the value of dispersion at distance $x = x_{max}$. Mean values of β_y are calculated separately for light (Table 12) and heavy particles,

the same as was done when considering empirical-formula dependencies. The mean value of β_y for heavy particles is $0.69 \cdot 10^{-4}$, and for light particles is $0.18 \cdot 10^{-2}$. Tables 12 and 13 present experimental values of $K_y = \beta_y u x_{max}$ for each track.

Table 13

Table of values of K_y for particles with settling velocities of $w = 1.1\text{-}2.65$ m/sec ($\alpha = 2.7$ g/cm^3)

Track No.	u	w	$\beta_y 10^4$	K_y experimental	K_y calculated
		$H = 500$ м			
7	4	1,1	1,55	1,05	0,50
8		1,35	1,13	0,66	0,41
9		1,55	1,02	0,57	0,36
10		1,80	1,40	0,67	0,39
1	15	1,35	0,52	4,45	5,72
2		1,55	0,68	5,20	4,98
3		1,8	0,14	1,03	4,29
		$H = 1000$ м			
11	3	1,35	1,1	0,69	0,46
12		1,55	0,68	0,39	0,40
13		1,80	1,66	0,85	0,34
14	3	1,1	0,5	0,27	0,67
15		1,35	1,22	0,59	0,46
16		1,55	0,58	0,26	0,40
17		1,8	0,66	0,26	0,34
18		2,0	0,5	0,18	0,31
19	4	1,35	0,53	0,61	0,81
20		1,55	0,38	0,38	0,71
21		1,8	0,38	0,35	0,61
22		2,0	0,72	0,58	0,55
23	4	1,1	0,78	1,12	1,0
24		1,35	0,22	0,28	0,81
25		1,55	0,68	0,82	0,71
26		1,8	0,72	0,72	0,61
27		2,0	1,06	1,02	0,55
4	5	1,35	0,25	0,53	1,28
5		1,55	0,30	0,54	1,11
6		1,80	0,28	0,48	0,96
30	6	2,0	0,38	0,73	1,23
31		2,2	0,80	1,44	1,13
32		2,4	0,47	0,82	1,01
28	10	2,0	0,35	0,88	3,45
29		2,2	0,28	0,98	3,13
		$H = 4000$ м			
33	5	1,55	0,64	3,68	4,45
34		1,8	1,44	7,63	3,84
35		2,0	0,73	3,37	3,45

Table 13 (Continued)

Track No.	u	w	$\beta_y 10^4$	K_y experimental	K_y calculated
36	5	1,35	0,36	5,01	5,11
37		1,55	0,64	5,09	4,45
38		1,8	0,5	3,5	3,84
39	6	2,4	0,98	4,71	4,14
40		2,35	0,7	3,82	5,35
			H = 7600 m		
41	6	2,4	0,65	5,36	7,21
			H = 8600 m		
41	5	2,0	0,77	7,16	6,9
42		2,2	0,86	7,57	6,57
43		2,4	0,52	4,60	5,75

The values of K_y for heavy particles, obtained by calculation from mean values of β_y, are given in Table 13 for comparison. It is obvious from the tables that the value of K_y for heavy particles had values from 0.2 to 7 m^2/sec, and for light particles from 80 to 700 m^2/sec. As was assumed, the value of K_y was dependent on the settling velocity of articles, altitude of the source and wind velocity. The largest values of K_y were observed for light particles in a strong wind and at high altitudes of the source.

Dependence of maximum concentration on K_x. It was shown above that within the assumed limits the location of maximum concentration as hardly dependent on the coefficient of longitudinal turbulent diffusion K_x. It is of interest to escalate the effect of K_x on the value of surface concentration at point $x = x_{max}$. Calculations by formula (10) at various values

of parameter $\frac{w^2K_x}{u^2K_z}$ indicate that this value hardly depends on K_x; thus, it varies within the limits 5-8% when the parameter $\frac{w^2K_x}{u^2K_z}$ varies from 0 to 0.02, and within the limits of 15-20% when $\frac{w^2\ K_x}{u^2\ Kz}$ varies from 0.02 to 0.20. It follows from this calculation that it is not possible to calculate the value of K_x, by relying only on the values of x_{max} and q_{max}.

Consideration of the theoretical layout and experimental data permitted calculating the value of the coefficients K_y and K_z and the role of coefficient K_x. A simple relationship was established between the coefficient of vertical particle dispersion K_z in the atmosphere and the location of maximum surface concentration of x_{max} and it was shown that the location of the latter and the value of q_{max} are barely dependent on K_x.

Comparison of calculated and experimental data indicated that calculated values of concentration at the point of the maximum is in most cases higher than those calculated experimentally. This is explained first of all by the imperfection of the theoretical scheme used, where particle loss by the settling cloud is not taken into account. That a loss does exist was often noted both during visual observations of the cloud from an aircraft and from ground data. We note that in those cases when cloud descent was not noted, calculated and measured values of maximum concentration are similar.

Conclusions

1. The paper considered dispersion in the free atmosphere of spherical particles with settling velocities from 0.07 to 1 m/sec and of irregular-shaped particles with settling velocities from 1 to 3 m/sec and releases from altitudes from 500-8000 meters from data of experiments in 1956-1957 and 1959-1960.

2. Empirical-formulas were obtained which permit calculation of the surface concentration of particles from an instantaneous point source, if source altitude, mean wind velocity and the operating layer, size and number of particles in the source are known:

a) the track at the surface for particles at an instantaneous point source develops in the direction of average wind in the layer of particle dispersion;

b) the location of the ground maximum of the surface concentration of particles in the range of velocities w investigated is determined by

the formula

$$x_{max} = x_{kine}\left[\sqrt{\left(\mu\frac{u^2}{w^2}\right)^2 + 1} - \mu\frac{u^2}{w^2}\right],$$

where $x_{kine} = \frac{uH}{w}$, and μ is the parameter dependent on stratification. The position of the maximum of heavy particles ($w > 1$ m/sec) is hardly affected by atmosphere turbulence, and in this case $x_{max} = x_{kine}$. The position of the maximum of surface concentration for light particles ($w = 0.07$-0.175 m/sec) is rather stable. Thus, at a source altitude of about 1000 meters and average wind velocity of 3-6 m/sec, the value of x_{max} comprises 30-40 source altitudes under conditions similar to neutral and slightly unstable stratification of the atmosphere;

c) the value of maximum surface concentration particles for the entire range of settling velocities investigated may be calculated by formula (5), wh[illegible] $= 2\cdot10^2$, $n = 1.4$, and transverse dispersion distribution of surfa[illegible]oncentration of particles along y at distance $x = x_{max}$ is calculated by formula (2), where $b_y = 1.14\cdot10^{-2}$ for particles with $w \geqslant 1$ m/sec and $b_y = 6.2\cdot10^{-2}$ for particles with $w \geqslant 0.2$ m/sec.

3. Calculation was made of the coefficients of turbulent particle dispersion K_x, K_y and K_z included in the semi-empirical equation of turbulent diffusion on the assumption that these coefficients are constant, but are expressed parametrically by u, H and w:

a) the coefficient of vertical particle dispersion K_z and the coefficient of transverse particle dispersion K_y may be calculated by the formulas

$$K_z = \frac{1}{2}\mu\frac{u^2 H}{w}, \quad K_y = \beta_y u x_{max}.$$

These formulas are valid when $\frac{u^2}{w^2} > 10^3$ for $w \geqslant 0.07$ m/sec. Here $\beta_y = 0.5\, b_y^2$;

b) the effect of particle dispersion coefficient K_x on development of the concentration of particles in the maximum zone is almost nonexistent, and, consequently, the value of K_x may not be calculated by the values of q_{max} and x_{max}. The coefficient of K_x may be ignored during practical calculations of the track in the zone of maximum concentration.

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13. ABSTRACT

The results of experimental investigations of solid particle dispersion from a source located in the atmosphere are considered Sand and plastic particles were employed as indicators to enable study of particle distribution on the earth's surface. Formulas are derived which permit the computation of particle surface density.

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